REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE

3. REPORT TYPE AND DATES COVERED
FINAL REPORT - 15 Aug 93 - 14 Feb 97

4. TITLE AND SUBTITLE
(AASERT-93) Field-Effect-Controlled, Coulomb-Blockage Single-Electron Transistor in Silicon

5. FUNDING NUMBERS
61103D
3484/TS

6. AUTHOR(S)

Professor Dimitri Antoniadis

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Department of Electrical Engineering
Massachusetts Institute of Technology
Cambridge, MA 02139

8. PERFORMING ORGANIZATION
AFOSR-TR-97
0149

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR/NE
110 Duncan Avenue Suite B115
Bolling AFB DC 20332-8050

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
F49620-93-1-0491

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

X-ray nanolithography for device fabrication was extended farther than previously reported. A new substrate photoelectron effect in x-ray nanolithography was observed. A way to circumvent this apparent limit to the resolution limits of x-ray nanolithography for real devices was found. Novel coulomb-blockade devices have been fabricated using this modified process. Preliminary measurements are underway on devices which should allow a better understanding of how the coulomb blockade disappears as coulping of the quantum dot to the environment increases via either a tunnel barrier or a quantum point contact.

19970602 054

14. SUBJECT TERMS

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	

Technical Report

AASERT - 93

F49620-93-1-0491

Field-Effect-Controlled, Coulomb-Blockade Single-Electron Transistor in Silicon

Dimitri Antoniadis, *Principal Investigator*
Professor of Electrical Engineering
(617) 253-4693

David Carter, *Research Assistant*
Graduate Student, Electrical Engineering and Computer Science

March 10, 1997

Final Technical Report
Period Covered: 8/15/93-8/14/96

Brief Report of Research Findings

Field-Effect-Controlled, Coulomb-Blockade Single-Electron Transistor in Silicon

Coulomb-blockade devices exploit the charging energy, $e^2/2C$, required to add a single electron to a small conducting island. Using nanofabrication technology, islands with small enough capacitance to the outside world can be made such that this charging energy is large compared to the thermal energy at low temperatures. Because the charge on the island can only change discretely in integer multiples of the electron charge, e, current through the island (via tunnel barriers) is impeded by the Coulomb charging energy required to add a *single* electron to it. Since this blockage of current can be controlled by a gate electrode, devices based on this effect have potential applications as amplifiers, detectors, and switches. In contrast to conventional field-effect transistor action, single-electron charging effects improve, rather than degrade, with shrinking dimensions.

Based upon our success with recent experiments [1,2,3] the AASERT student has continued to work on coulomb-blockade devices in GaAs/AlGaAs (quantum dots). Measurements on a quantum dot with three leads and on a coupled quantum dot system have led us to believe that important questions still remained unanswered about the behavior of individual and coupled quantum dots. Of particular interest to the research community and for the prospects of computation with real coulomb blockade structures is how the transport properties of individual or coupled quantum dot structures change as the dot goes from being weakly coupled to its environment (therefore having a well-defined charge) to being strongly coupled to its environment (therefore not having a well-defined charge). The student has pursued fabrication of a device which would allow investigation of the transition between these two regimes.

Previous experiments in semiconductor structures have focused on quantum dots which are coupled to their environment or to each other via quantum point contacts (QPC's). As these QPC's are opened to allow the dot to couple to its electronic environment, a single electron transport channel opens up. When one transport channel is opened fully (such that its transmission probability is equal to unity), the quantum dot no longer has a well-defined charge state and coulomb blockade effects disappear.

The student has fabricated a novel type of quantum dot structure in which the transition from poor environmental coupling to strong coupling happens not through the opening of one channel to a transmission of unity, but through the opening of many channels to a small transmission probability. In this case the physics of the transport will be much more like that of a metal tunnel barrier, like those used in Josephson junctions or metal coulomb blockade devices. Fig. 1 shows the two types of double-dot structures, one with a QPC between the dots and one with a fine-line tunnel barrier between them. By fabricating both devices on the same chip, a number of experiments can be done comparing the behavior of the two barrier types in single and double-dot configurations.

In order to fabricate the tunnel barrier structure in such a way as to have good control over the strength of the barrier with an external voltage source, it is necessary to have extremely fine lines. In order to push these widths as low as possible, it was decided to use x-ray nanolithography, which has no line-widening effects due to backscattered electrons from the semiconductor substrate as is found in an electron-beam direct write process. In choosing to use x-ray nanolithography for device fabrication, we were pushing the full x-ray fabrication process further than it had ever been pushed before.

A new x-ray "mother" mask was written at the Naval Research Laboratory. This mask was processed in our laboratory and has linewidths down to 42 nm. An SEM micrograph of a device from this mask is shown in Fig. 2a.

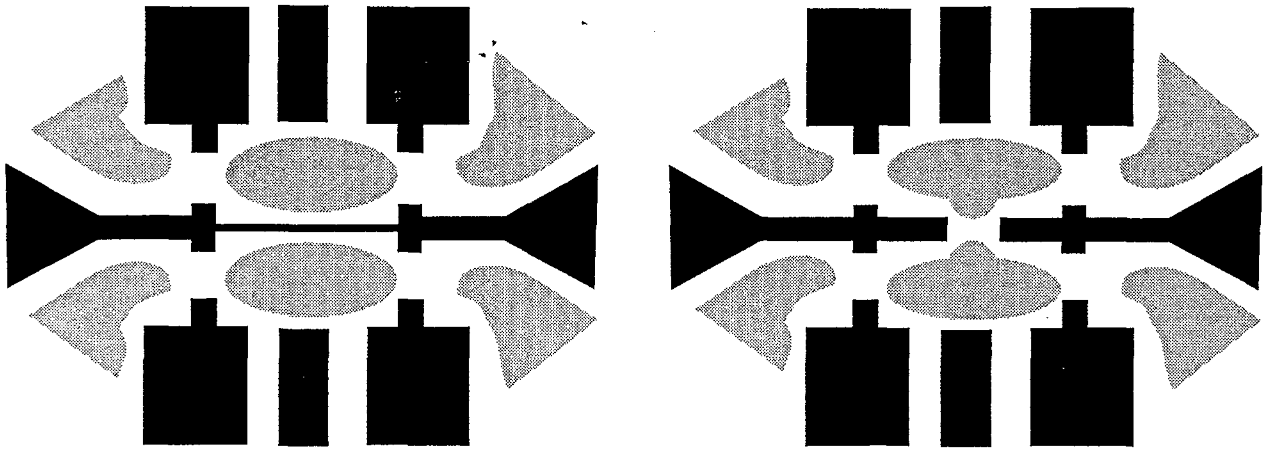
In order to print a device from this mask, a negative replica or a "daughter" mask had to be made. In the fabrication of this "daughter" mask, the "mother" mask is used to create a PMMA mold into which gold is electroplated. The 42 nm gold line on the mother becomes a PMMA line on the daughter with an approximately 40 nm width, 200 nm height, and 500 nm length. We had problems in our many attempts to create this "daughter" in getting this fine line of PMMA to adhere during the development and plating process. We were finally able to track the adhesion problems to a substrate photoelectron effect – x-rays which are absorbed strongly in the gold plating base on the daughter mask generate photoelectrons which make their way into the bottom layer of the PMMA and create additional dose in the resist. This effect apparently has a lateral range of approximately 20 nm which is enough to undercut a 40 nm line and prevent it from adhering. The effect had not been seen before because lines wider than 40 nm on daughter masks were able to adhere and the plated mask and devices printed from it looked fine. It was only in pushing the full device fabrication process with x-ray lithography that this substrate photoelectron effect was discovered [4].

Once the effect was understood a way around it was found – use a thinner gold plating base (approximately one monolayer) to minimize the generation of photolecetrons. By absorbing fewer x-rays in the plating base, less extra dose is given to the resist interface layer. An SEM micrograph of a device on the daughter mask is shown in Fig 2b.

Devices have been fabricated using this "daughter" mask. an SEM micrograph of such a device is shown in Fig. 2c. Preliminary measurements are underway on these devices. Further experiments and simulations are also underway to better understand and control the susbstrate photoelectron effect.

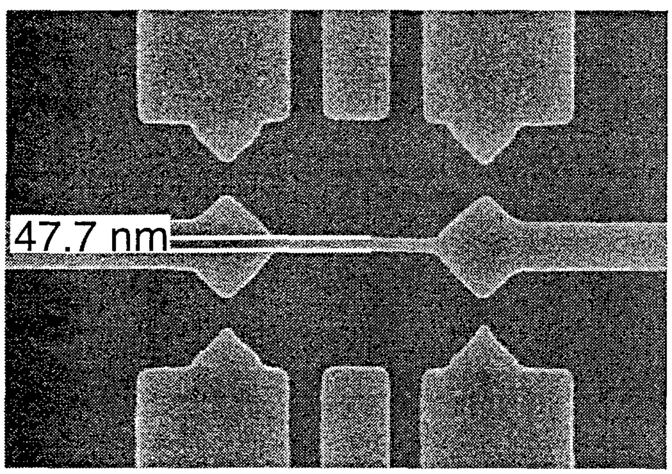
In summary, the AASERT student has pushed x-ray nanolithography for device fabrication farther than it had been pushed previously. A new substrate photoelectron effect in x-ray nanolithography was observed. A way to circumvent this apparent limit to the resolution limits of x-ray nanolithography for real devices was found. Novel coulomb-blockade devices have been fabricated using this modified process. Preliminary measurements are underway on devices which should allow a better understanding of how the coulomb blockade disappears as coulping of the quantum dot to the environment increases via either a tunnel barrier or a quantum point contact.

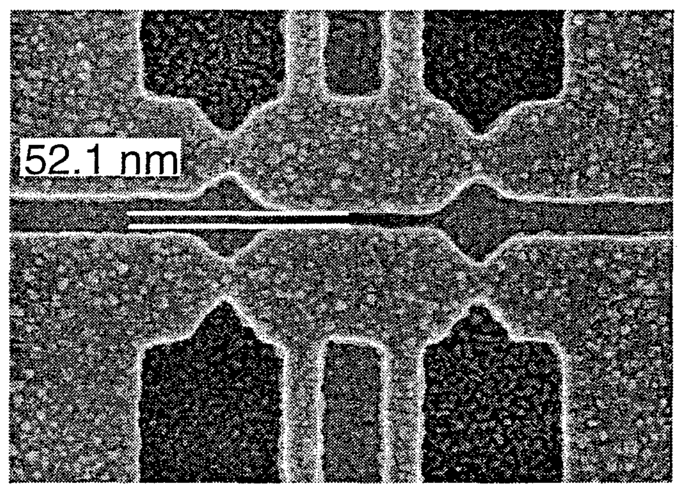
[1] A. Kumar, C.C. Eugster, T.P Orlando, D.A. Antoniadis, J.M. Kinaret, M.J. Rooks, and M.R. Melloch, *Correlation of Oscillations in a Quantum Dot with Three Contacts*, Appl. Phys. Lett. **66**, 1379.
[2] M. Burkhardt, D.J. Carter, D.A. Antoniadis, T.P. Orlando, H. I. Smith, M.R. Melloch, K.W. Rhee, and M.C. Peckerar, *Coulomb Blockade Effects in Double Quantum Dots*, presented at the March 1995 Meeting of the American Physical Society, San Jose, CA.
[3] M. Burkhardt, D.A. Antoniadis, T.P. Orlando, H. I. Smith, M.R. Melloch, K.W. Rhee, and M.C. Peckerar, *Fabrication Using X-Ray Nanolithography and Measurement of Coulomb Blockade in a Variable-Size Quantum Dot*, J. Vac. Sci. Technol. B **12**, no. 6, pp. 3611-3613.
[4] D.J.D. Carter, A. Pepin, M.R. Schweizer, Henry. I. Smith, and L.E. Ocola, *Substrate Photoelectrons in X-ray Nanolithography*, submitted to the 41st International Conference on Electron, Ion, and Photon Beam Technology and Nanofabrication, May 27-30, 1997.



(a) Fine Line **(b) QPC**

Figure 1: a) Coupled quantum dot device with a fine line serving as the barrier between the dots.
b) Device with a quantum point contact as barrier. As the two types of barriers open up the physics of the transport should be quite different.





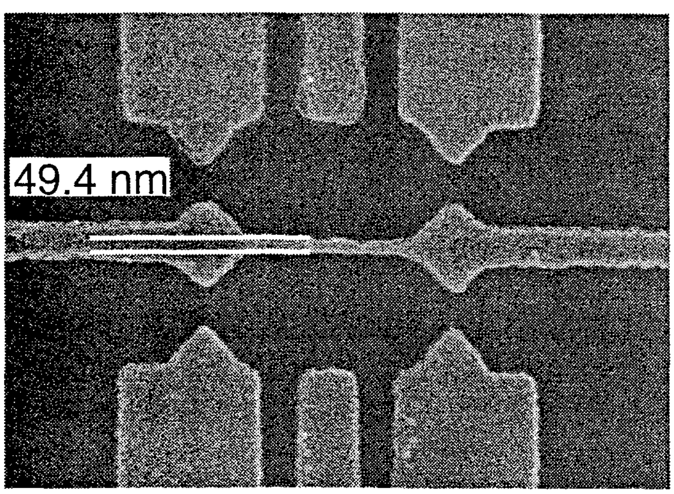


Figure 2:
a) "Mother" mask written by electron beam at Naval Research Laboratory. (Au on SiNx membrane)
b) "Daughter" mask fabricated with newly-modified process for ultra-fine lines from the above "mother". (Au on SiNx membrane)
c) Coupled quantum dot device fabricated with above "daughter" (AuPd on GaAs)